TIDAL DEFORMATION AND TIDAL DISSIPATION IN EUROPA. W. B. Moore, *Department of Earth and Space Sciences, University of California, Los Angeles, Los Angeles, CA 90095-1567, USA.*

Tidal forces have played a dominant role in the evolution of the inner three Galilean satellites of Jupiter. From the assembly of the Laplace resonance to the volcanic activity of Io, tidal forces orchestrate the dynamics and evolution of Io, Europa, and Ganymede. In Europa's ice shell, tidal deformation may directly drive surface tectonics, while tidal dissipation within the shell may indirectly lead to surface modification. Tidal forces may also lead to non-synchronous rotation of the shell or even true polar wander through torques acting on asymmetries in the shape of the shell.

Tidal Deformation of Europa's Ice Shell

The presence of a liquid ocean beneath Europa's ice shell essentially determines the tidal response of the shell. Since the ocean has no mechanical strength, it flows in response to the tide, attempting to match the changing shape of the equipotentials. Unless the shell is very thick and strong, it cannot effectively limit the motion of the underlying liquid, therefore the deformation of the shell very nearly matches that of the liquid, and is independent of the thickness or strength of the shell to within a few percent, for shells less than about 100 km thick. The stresses in the shell are primarily dependent on the strength of the shell, since the deformation is determined by the fluid response. Since we do not know the rigidity of ice under Europan conditions to within a factor of 10, the stresses in the shell are equally uncertain.

The tidal deformation of Europa's ice shell is determined by solving the equations of motion for a layered Maxwell-viscoelastic body in a time varying gravitational potential [*Moore and Schubert*, 2000]. The interior of Europa is modeled as several uniform layers and is completely specified by the radii of the layers and the values of density, viscosity and shear modulus in each layer. Liquid layers have zero shear modulus and are treated as inviscid since the viscosities of liquid iron and liquid water are very small. A liquid core is assumed in the calculations presented here. The effect of a solid core is to reduce deformation by several percent. The parameters of the basic model are given in Table 1. The densities are constrained by the hydrostatic models which best fit the observed gravitational field of Europa [*Anderson et al.*, 1998].

Table 1: Europa Interior Model.

Layer	thickness [km]	density [kg m^{-3}]
core	704	5150
mantle	742	3300
ice/ocean	119	1000

In a Europan reference frame, the time-varying potential to first order in the eccentricity is given by [*Kaula*, 1964]:

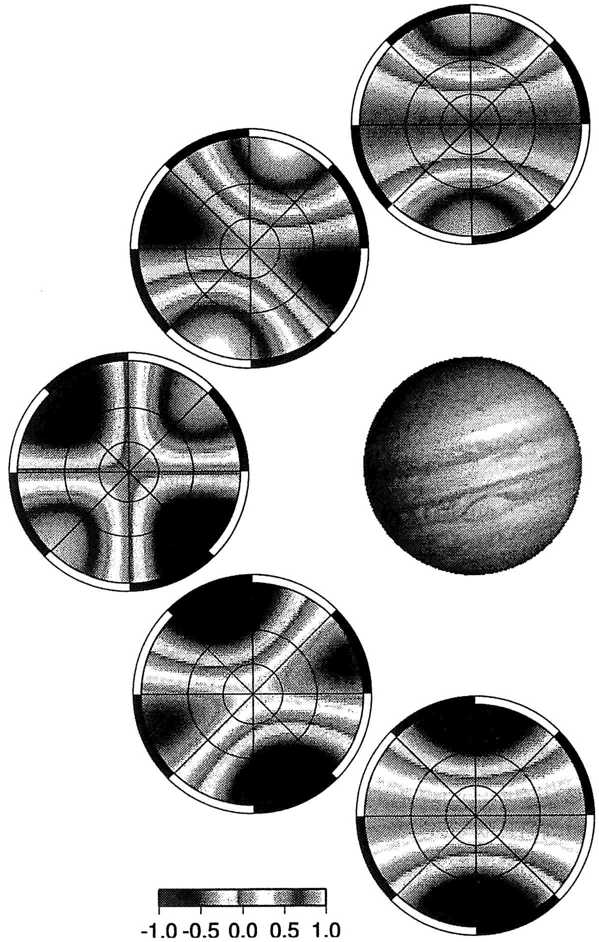

Figure 1: Φ from (1) normalized to ± 1 plotted over the northern hemisphere of Europa beginning at perijove (top) and proceeding counter-clockwise to apojove. The direction to Jupiter is indicated by the image.

$$\Phi = r^2 \omega^2 e \left\{ -\frac{3}{2} P_2^0 (\cos\theta) \cos\omega t + \frac{1}{4} P_2^2 (\cos\theta) \left[3\cos\omega t \cos 2\phi + 4 \sin\omega t \sin 2\phi \right] \right\} \quad (1)$$

where r is radius from the center of Europa, ω is the orbital angular frequency (2.05×10^{-5} rad s^{-1}), e is the orbital eccentricity (0.0093), θ and ϕ are the colatitude and longitude with zero longitude at the sub-Jovian point, t is time, and P_2^0 and P_2^2 are associated Legendre polynomials.

Figure 1 is a normalized map of Φ as given by (1) over one half of a Europan orbit starting at perijove (top left) and proceeding counter-clockwise. The remainder of the orbit is a reflection of the first half. Except for a scale factor (usually given as Love numbers) and a possible phase lag, Figure 1 also represents the radial surface displacement u_r and the perturbation to the force of gravity Δg. Table 2 gives the maximum

Table 2: Love numbers and peak radial deflection.

D [km]	μ [Pa]	h_2	k_2	u_r [m]
0	0	1.26	0.261	29.6
1	10^9	1.26	0.261	29.6
10	10^9	1.25	0.259	29.3
100	10^9	1.16	0.241	27.2
1	10^{10}	1.25	0.259	29.3
10	10^{10}	1.16	0.241	27.2
100	10^{10}	0.669	0.141	15.7
		no ocean		
119	10^9	0.0271	0.0149	0.636
119	10^{10}	0.0252	0.0144	0.591

values of u_r as well as the surface Love numbers h_2 and k_2 for models of Europa's rheological structure with varying ice thickness D and shear modulus μ. The surface Love numbers are defined by:

$$h_2 = \frac{g_0 u_r}{\Phi} \quad and \quad k_2 = \frac{\Phi_{tidal}}{\Phi} \tag{2}$$

where g_0 is the acceleration of gravity at the surface, and Φ_{tidal} is the potential that results from the deformation of Europa. For the fluid/elastic models in Table 2 there are no phase lags. Visco-elastic behavior can cause the tidal response of Europa to lag the disturbing potential.

Tidal Dissipation

Phase lags in the tidal response due to visco-elastic behavior also lead to dissipation of tidal energy in the form of heat within Europa's ice shell. Using the same solutions presented above, the dissipation rate can be computed from

$$\frac{dW}{dt} = \sum_{ij} \sigma_{ij}(t)\, \dot{e}_{ij}(t-\tau) \tag{3}$$

where dW/dt is the power dissipation rate, σ is the stress tensor, $\dot{e}$ is the strain rate tensor, and τ is the phase lag. If the phase lag is zero (purely elastic response), the sum goes to zero because σ and $\dot{e}$ are perfectly out of phase. From the constitutive relation for a Maxwell visco-elastic body:

$$\dot{e}_{ij} = \frac{1}{\mu}\dot{\sigma}_{ij} + \frac{1}{\eta}\sigma_{ij} \tag{4}$$

it is clear that the viscosity η is the critical parameter controlling dissipation. Since the viscosity of ice is very dependent on temperature, the heat production in the ice shell cannot be decoupled from the heat transport, and the two processes must be modeled in a self-consistent way.

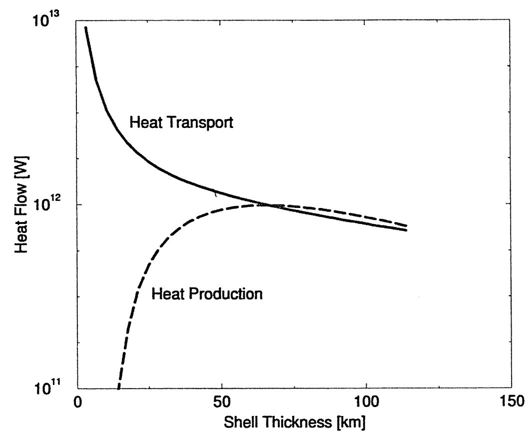

Figure 2: Heat transported by convection (solid line) vs. heat produced by tidal dissipation (dashed line) for a set of self-consistent temperature profiles in a Europan ice shell.

One means of achieving a self-consistent model is to use a convective parameterization to establish the temperature structure in a shell of a given thickness. The heat transported by convection can then be compared with the heat produced by tidal dissipation in a shell with the same temperature structure. An example of such a calculation is shown in figure where the heat transport is given by the solid line and the heat production by the dashed line for ice shells of different thickness on Europa, using the temperature- and stress-dependent grain boundary sliding rheology of *Goldsby and Kohlstedt* [2001], and the convective parameterization of *Solomatov and Moresi* [2002]. There exists an equilibrium between heat production and heat loss in this case for a shell thickness of about 70 km.

References

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